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# Investigation of Geometric Effects on the SMARTweave Signal

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and Shawn M. Walsh

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# **Army Research Laboratory**

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**Clarissa J. DuBois, William O. Ballata, Shawn M. Walsh**  
Weapons and Materials Research Directorate, ARL

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## **Abstract**

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SMARTweave or Sensors Mounted As Roving Threads is an electrical grid comprised of orthogonal noncontacting conductive filaments used primarily to monitor the resin flow in the manufacturing of liquid-molded composite materials. It works on the principles of the half Wheatstone bridge and ionic mobility. It has been successfully demonstrated as a technology, but now the challenge is to characterize the system and its behaviors. The variables addressed in this report are basically geometric in nature. The following will each be investigated: the sensor materials and their perpendicular area of conduction, the separation from one node to the next in the horizontal plane, and the separation from one lead to the next in the vertical plane. Results are presented regarding the SMARTweave sensor materials and signals. The results on horizontal spacing, the area of conduction, and vertical separation will be presented.

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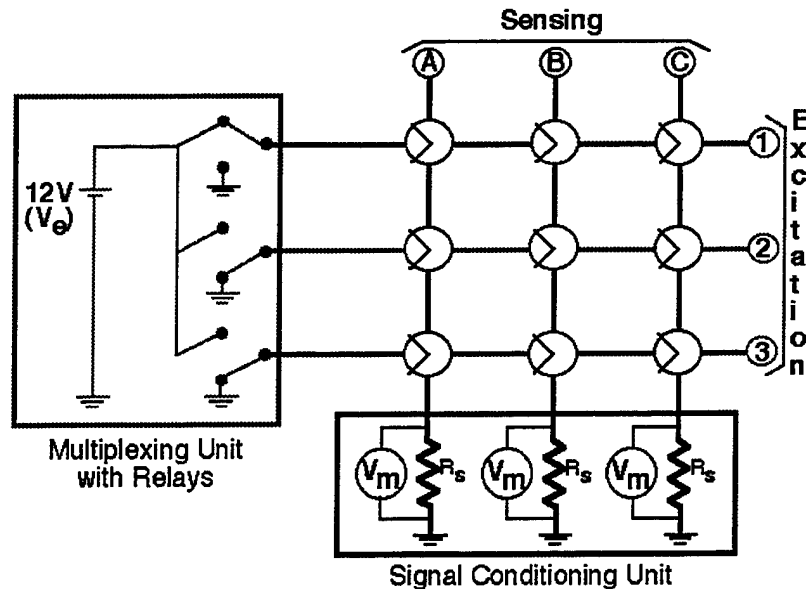
# **1. Introduction**

SMARTweave or Sensors Mounted as Roving Threads is an electrical grid comprised of orthogonal noncontacting conductive filaments used primarily to monitor the resin flow in the manufacturing of liquid-molded composite materials. It works on the principles of the half Wheatstone bridge and ionic mobility. It has been successfully demonstrated as a technology, but now the challenge is to characterize the system and its behaviors. The variables addressed in this report are basically geometric in nature. The following will each be investigated: the sensor materials and their perpendicular area of conduction, the separation from one node to the next in the horizontal plane, and the separation from one lead to the next in the vertical plane. To begin, the SMARTweave system will be described in detail. Second, SMARTweave sensor materials and signals will be discussed. Next, the research on horizontal spacing, the area of conduction, and vertical separation will be presented. Finally, conclusions based on the results will be drawn.

## **2. SMARTweave System**

The SMARTweave system consists of two planes of conductive threads in an orthogonal noncontacting grid. The two layers are separated by the permeable, yet insulative, plies of the fabric preform. A 12-V direct current (DC) signal is sent through one of the planes of sensors, which are called "excitation lines." The polymeric resin material, which serves as the matrix for the composite, contains ions that are free to move within the fluid. SMARTweave uses this fact; therefore, as the resin fills the preform, the two planes of sensors form a series of connected circuits through the impregnated composite. The second plane of sensors measures the voltage that can cross the gap between the two planes, called "sense lines." Figure 1 depicts the general circuit schematic for the SMARTweave system. Since a direct current is used, only the ionic mobility of the resin is being measured.

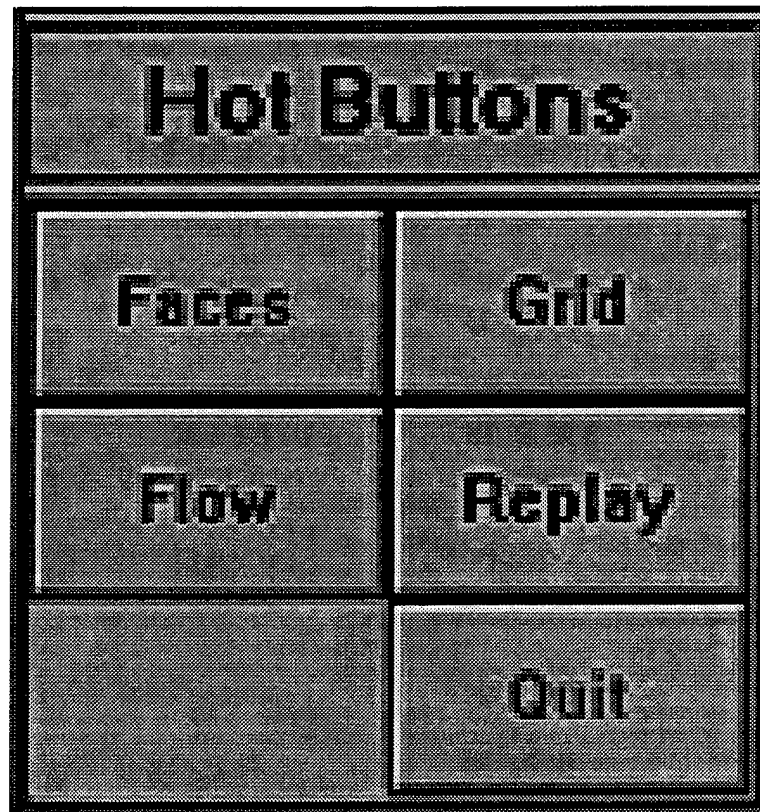
The SMARTweave system consists not only of the electrical sensing grids but also a series of hardware and software components. First, the excitation unit, which was custom-made for the U.S.



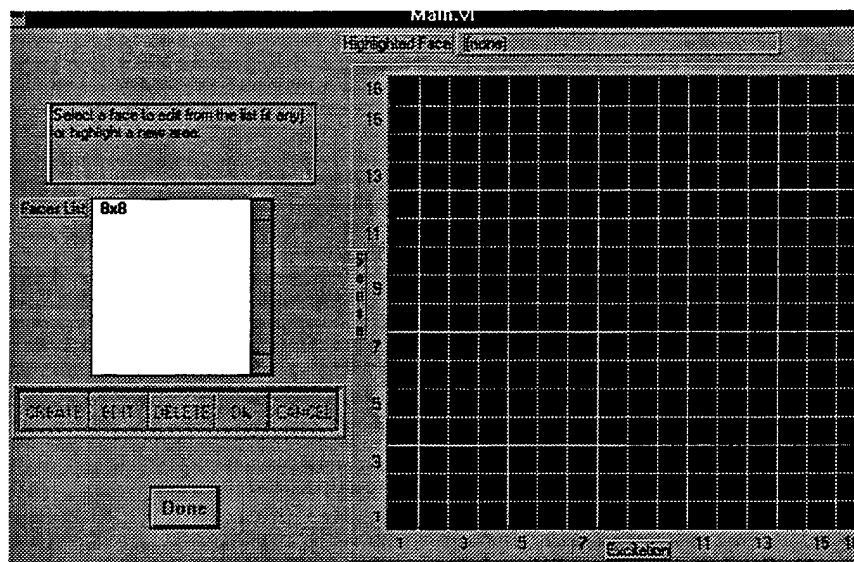
**Figure 1. SMARTweave Circuit Diagram. This Is the Generalized Circuit of How the SMARTweave System Operates.**

Army Research Laboratories by Waibel Technical Computing (WTC), contains the 12-V DC power supply, as well as mechanical relays used to switch from one excitation line to another. A National Instruments SCXI-1000 Chassis with a 1,300 module controls the sense lines. A Dolch L-PAC 586 portable computer is used to collect and analyze the data. Finally, the SMARTweave software program was written by WTC on National Instruments LabVIEW Version 3.0. Sixteen sense and 16 excitation lines were made of shielded cable, all of which had 1-in copper (Cu) alligator clips as connectors. Each excitation and sense line was assigned a number from 0 to 15. All intersecting lines were then labeled according to their nodal coordinates (i. e., sense no., excitation no.). All data were taken and recorded to correspond to this ranking.

The user is faced with five main options upon entering the SMARTweave software package, as depicted in Figure 2. The sampling rate may be defined in the grid or flow screen. At this point, the system has a maximum capacity of a 16-excitation by 16-sense line for a total of 256 nodal locations. However, not all sensors must be used at once. In the faces option, the user may define not only the number of sensors to be used to collect data but also the geometry of the grid orientation. Figure 3 illustrates the faces screen seen by the operator. In this case, an  $8 \times 8$  grid has been chosen.

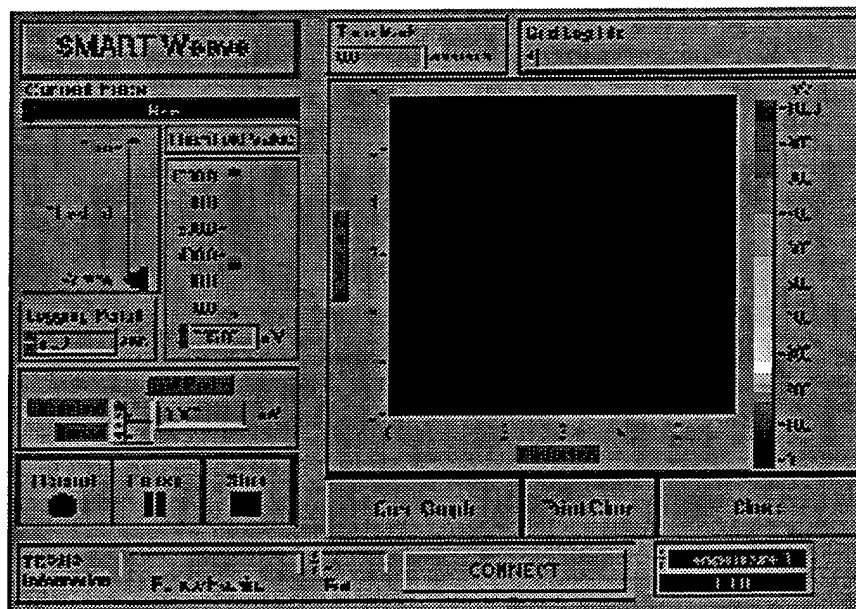


**Figure 2. Hot Buttons Initial SMARTweave Screen.**

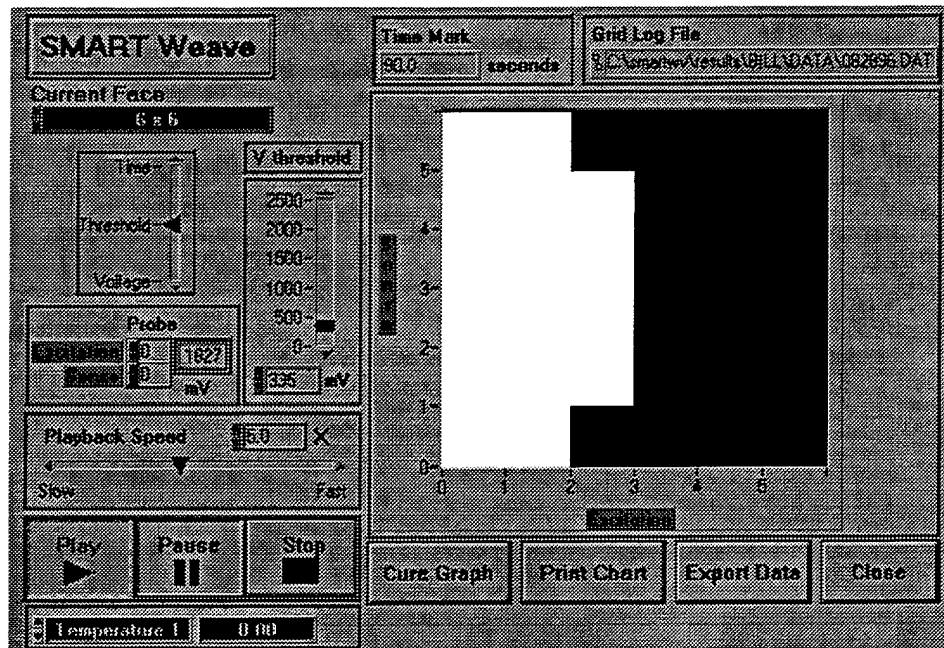


**Figure 3. The Faces Option That Allows the User to Define the Size of the Grid and/or Multiple Faces.**

In the flow screen depicted in Figure 4 ( $6 \times 6$  face), each block corresponds to a specific voltage at the respective node. The flow front of the resin may be depicted on this flow graph. Not only can one view the overall picture of the resin infusion but also one may focus upon the voltage value at individual nodes using the grid probe. The cure graph displays real-time, voltage-vs.-time data for any series of user-defined node combinations. The logging period or scan rate, file name, and elapsed time are also recorded. The elapsed time may be defined to correlate with any zero time, such as initial point of infusion or addition of the catalyst in order to judge time until gelation. Once the data have been recorded, the portable system has the option of replaying the data at any time. Figure 5 shows the replay screen, which has many of the same features as the flow screen, including overall flow, grid probe, and cure graph. In this example, a center point infusion and vacuum source, along the last excitation line, was tested. SMARTweave monitored the semicircular flow pattern induced by the experimental setup, using glass preform and a vinyl ester resin. The data may also be exported in text format with a defined amount of data points. Another feature of the replay screen is the ability to view thermal profiles recorded using a series of thermocouples, which are independent of the SMARTweave grid.



**Figure 4. The Flow Screen ( $6 \times 6$  Face), Where the Data Acquisition, Recording, and Display Takes Place.**

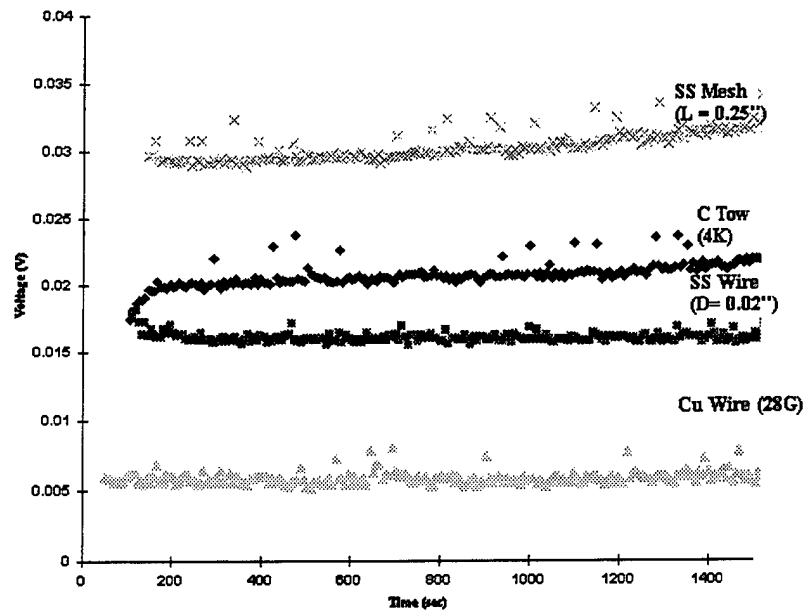


**Figure 5. The Replay Screen, Where Previously Recorded Data Can Be Replayed and Analyzed.**

This entire package was entitled the “portable SMARTweave system.” This was because it is completely portable and can be checked as luggage and brought to any location.

### 3. SMARTweave Sensor Materials and Signals

In order for SMARTweave to sense a voltage signal, the fluid between the grid must be conductive. By measuring the ionic mobility of the fluid, the relative voltage across the node junction was measured. The magnitude of the final SMARTweave signal is not only dependent upon the conductivity of the resin system but also upon the individual sensor’s material and geometry. Figure 6 depicts the SMARTweave signal of the four different sensor types tested: a 0.25-in-wide stainless steel mesh, a 4k carbon tow, 28-gauge bare Cu wire, and 0.020-in bare stainless steel wire. All trials were conducted in the same 0.75-in hole with 5 ml of Derakane 411-C50/0.02 weight-percent CoNAP, a cobalt naphthlate salt solution, and a constant separation distance of 0.105 in. As shown above, the voltage appears to be a function of the type of material and area of



**Figure 6. The SMARTweave Signal Differences for Various Sensor Materials.**

the sensor. It has also been shown that both horizontal and vertical sensor separation influence the voltage signal. By isolating each of these variables, their individual effect on the magnitude of the SMARTweave signal was determined.

Numerous sensor types have been tested for use in the SMARTweave grid. These include 28-gauge bare Cu wire; 28-gauge bare Cu wire wrapped in finely braided E-glass; E-glass wrapped with a thread of Cu wire; 0.02-in stainless steel wire; 4, 8, 12, 16, and 20k unsized and sized carbon tows; 0.125-, 0.25-, and 0.50-in stainless steel mesh; and a 0.06-in graphite line. The sensors for this study were chosen based upon the following criteria in order of importance: (1) strength of SMARTweave signal, (2) economical considerations: cost/length and cost of lay-up labor, (3) reactivity in resin system, (4) change of conductivity per length before and after fluid infiltration, (5) change of material properties with sensor in place, (6) damage detection opportunities, and finally, (7) grid spacing flexibility.

## 4. Horizontal Separation Distance

The horizontal interactions of four sensor materials were tested: 0.25-in-wide stainless steel mesh, a 4k carbon tow, 28-gauge bare Cu wire, and 0.020-in stainless steel wire. In order to isolate each sensor's effective area

$$R/(r_v l) = A_{\text{eff}}, \quad (1)$$

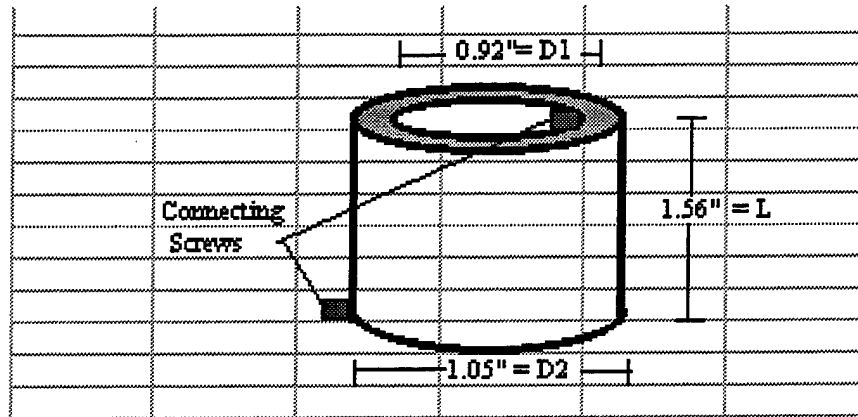
the resistivity,  $r_v$ , of the noncuring (Dow's Derakane 411-C50/0.2 weight-percent Mahogany's CoNAP) and curing resin (Dow's Derakane 411-C50/2.0 weight-percent Akzo's Trigonox 239A/0.2 weight-percent Mahogany's CoNap) systems was determined.

**4.1 Resistivity of Resin - Experimental Methods.** First, an aluminum resistivity cell was machined according to ASTM Standard D4496 (10.02), as shown in Figure 7. Tacky tape was wrapped around a Teflon washer in order to seal the bottom of the resistivity cell. A 500-ml master batch of the uncatalyzed resin was used to do the experiment; it consisted of Dow's Derakane 411-C50, and 0.2 weight-percent CoNap was prepared (520.0-g vinyl ester, 1.06-g CoNap [a Metler 240 balance was used to mass samples]) and stored under dark conditions at room temperature. The resin was inserted into the test cell in a circular pattern using a 10-cm<sup>3</sup> syringe with a 20-gauge syringe tip to prevent air from being trapped between the walls of the cell. Node (0,0) of the SMARTweave system was attached to the screws in the resistivity cell with Cu alligator clips to measure the voltage drop across the cell for all trials. An 8-s time interval between voltage readouts was selected. The recorded voltage data are an average over the elapsed time. A Keithley 617 electrometer was used to verify the voltage readings from the portable SMARTweave system. At this point, the nomenclature used is defined as:

$A_{\text{eff}}$  = Effective nodal area [=] m<sup>2</sup>.

$D$  = Diameter of stainless steel wire [=] in.

$D_1$  = Diameter of inside cylinder of resistivity cell [=] in.



**Figure 7. Concentric Aluminum Cylinder Resistivity Cell (ASTM Standard D4496 [10.02]) Used to Determine Volumetric Resistivity.**

$D_2$  = Diameter of outside cylinder of resistivity cell [=] in.

$l$  = Vertical separation distance [=] in.

$L$  = Height of resistivity cell [=] in.

$R$  = Resistance [=]  $\Omega m$ .

$R_j$  = Junction resistance [=]  $\Omega m$ .

$R_v$  = Volumetric resistance between cylinders of resistivity cell [=]  $\Omega m$ .

$V_D$  = Drop voltage [=] V.

$V_e$  = Excitation voltage [=] V.

$r_v$  = Volumetric resistivity [=]  $\Omega m$ .

With the voltage data and dimensions of the cell, the volumetric resistivity was calculated.

$$r_v = [2pLR_v]/[\ln (D_1/D_2)] , \quad (2)$$

where  $D_1$  = the diameter in inches of the inside cylinder,  $D_2$  = the diameter of the outer cylinder in inches, and  $L$  = the height of the resistivity cell, also in inches. The drop voltage or  $V_D$  was then converted into a resistance through:

$$R_j = [(V_e R_D)/V_D] - R_D. \quad (3)$$

The excitation voltage or  $V_e$  remained constant at 12 V. A 10-MW drop resistor  $R_D$  was used. For the resistivity cell, the volumetric resistance,  $R_v$ , was assumed to equal the junction resistance,  $R_j$ .

$$R_v = R_j \quad (4)$$

Characteristic measured voltages and calculated junction resistances can be found in Figure 8. Both values depict a sharp change initially. Before the voltage is excited through the cell, the ions in the resin are in an equilibrium state. However, after the resin has been excited, the ions, primarily the cobalt free radical, migrate toward the negatively charged wall of the cell. The cobalt ion's migration cause the sharp increase in voltage and decrease in resistance. The leveling of the curve occurred as the ions reached a new equilibrium state. An average of the junction resistances was taken as the slope of  $V_D$  vs. time ( $\sim 0$  mV/s) until the end of the trial. The final averaged volumetric resistivity equaled  $7.00 \times 10^6 \Omega\text{m}$  as calculated in Table 1.

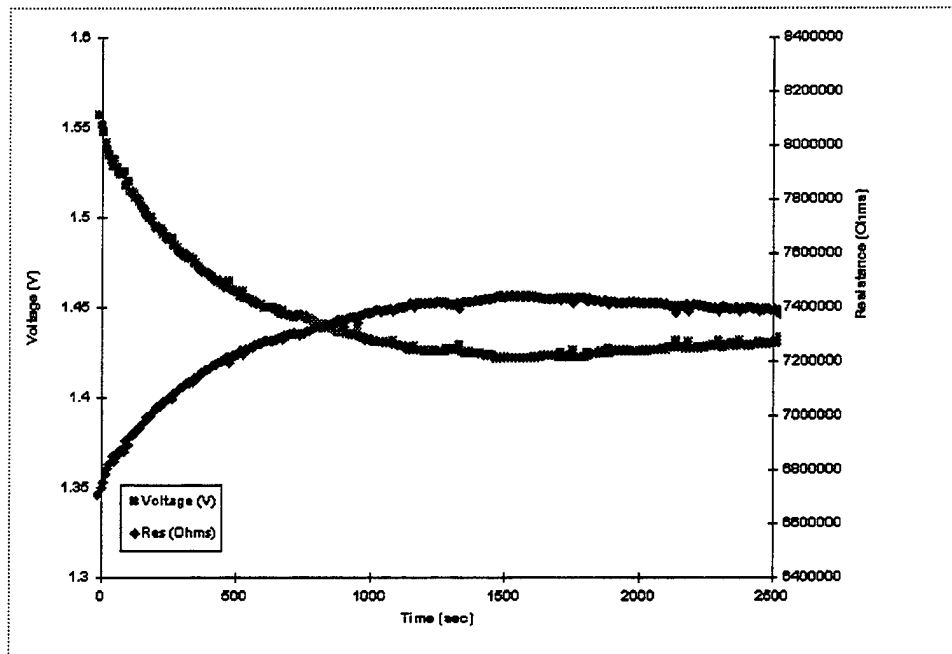


Figure 8. Double Y Plot, Showing the Relationship of Voltage and Resistance.

**Table 1. Resistivity Values of Derakane 411-C50/0.02 Weight-Percent CoNap Found Using Resistivity Cell and SMARTweave Portable System**

Trial	Resistivity ( $\Omega\text{m}$ )	Standard Deviation ( $\Omega\text{m}$ )
1	7.42E + 06	1.40E + 04
2	6.55E + 06	9.00E + 03
3	7.03E + 06	9.50E + 03
Average	7.00E + 06	1.08E + 04

**4.2 Effective Area of Sensor Material - Experimental Methods.** With the calculated volumetric resistivity, the junction resistance was related to the actual vertical separation distance,  $l$ , of the SMARTweave grid and the effective area,  $A_{\text{eff}}$ , of each node.

$$R = r_v ( l / A_{\text{eff}} ) \quad (5)$$

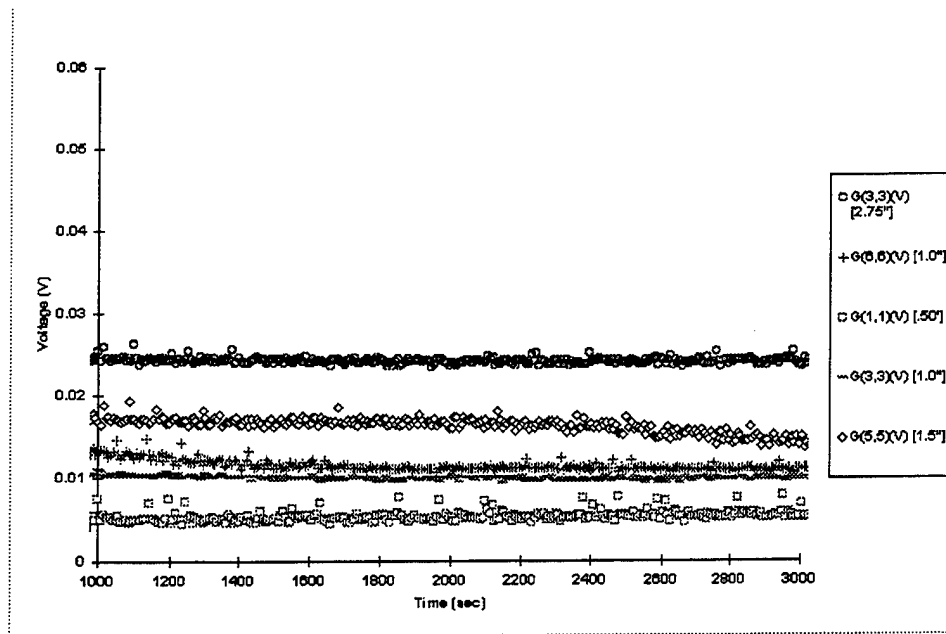
The area in this case is not necessarily the actual nodal area, but rather extends larger than the node. The charge did not necessarily travel in a straight path perpendicularly from the excitation line to the sense line. Therefore, the area determined is better defined as an effective area, covering a wider portion of the actual sensor. Holes ranging from 0.25 to 3.0 in at 0.25-in increments were drilled in uniformly thick composite plates. The composite plates were rinsed before and after each trial with acetone to remove any residue. The noncuring master batched resin from the resistivity trials was used for all tests. The excitation leads were attached flush to the top of the plate. A wall of tacky tape was used to surround the hole and prevent any resin leakages. The sense leads were adhered to the bottom of the plate with tacky tape, and the entire plate was sealed with a layer of vacuum bagging. The diameter of the layer of tacky tape on the top was determined so that there would be an equal amount of resin above and below each of the sensor leads. After baseline was established on the voltage-vs.-time graph of the SMARTweave system, the master batched resin was inserted. Table 2 lists the hole diameters with their respective volume of uncured resin.

**Table 2. Amount of Resin Added to Each Hole Size of Effective Area Comparison**

Hole Diameter (in)	Resin Volume (ml)
0.25	5
0.50	5
0.75	5
1.00	5
1.25	5
1.50	8
1.75	15
2.00	18
2.75	20
3.00	20

### **4.3 Results and Discussion.**

**4.3.1 Voltage vs. Time.** As the hole diameter increased, the total sensor surface area exposed to the resin also increased. Since the magnitude of the signal is related to the mobility of the ions in the resin system, in this case the Cobalt ions, a greater surface area drawing the ions toward or pushing them away would cause an increased probability for the ions to move across from the excitation line to the sense line. Therefore, as the hole diameter increases, the SMARTweave signal increases, as shown in Figure 9. The voltage was constant over time, since the noncuring vinyl ester resin system was used. In other words, the ionic mobility remained relatively constant throughout the entire time tested. The initial increase in voltage was caused by the infusion of resin and, as in the resistivity cell, the drifting of Cobalt ions. Once the Cobalt salt reached an equilibrium state, the signal stabilized.



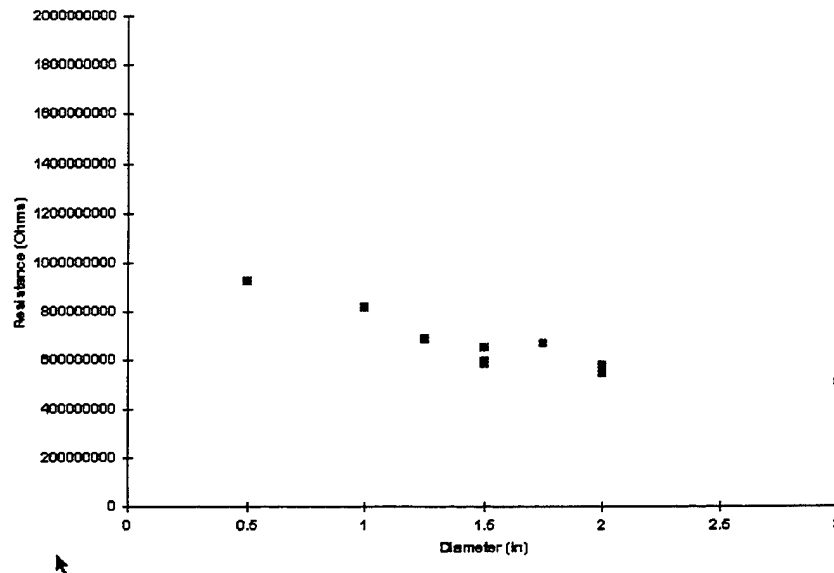
**Figure 9. Voltage of SMARTweave Signal for Several Different Hole Diameters.**

All four sensor types behaved similarly to the stainless steel mesh; however, there was a significant difference in SMARTweave signals between the four sensor types. Table 3 summarizes the voltage variances. For all hole diameters tested, the stainless steel mesh had the greatest voltage signal. The carbon tow was between 18–20% below that of the mesh. The Cu wire’s voltage signal was consistently 60% below that of the stainless steel mesh. Finally, the stainless steel wire’s voltage remained ~70% below that of the mesh of the same material. The voltage trend seemed to increase with the sensor surface area. However, the exposed surface area alone was not the only explanation for the increased voltage, since the stainless steel wire with a smaller voltage signal had a larger diameter of 0.02 in compared to the diameter of the 28G Cu wire at 0.125 in. The conductivity of Cu is greater than that of stainless steel at  $6.0 \times 10^7 (\Omega\text{m})^{-1}$  vs.  $1.4 \times 10^6 (\Omega\text{m})^{-1}$ , respectively. In this case, the conductivity of the two materials influenced the voltage signal.

**4.3.2 Hole Diameter vs. Resistance.** The resistance decreased as the hole diameter increased. As shown in Figure 10, the resistance decayed in the uncured resin with the 28G Cu wires as sensors. By extrapolating the curve to a flat region, the minimum horizontal separation distance between sensors may be found. Dependent upon the individual sensor type, each sensor material

**Table 3. Comparison of the SMARTweave Signal at Varying Hole Diameters for the Different Sensor Materials**

Diameter (in)	Stainless Steel Mesh (mV)	Carbon Tow (mV)	Cu Wire (mV)	Stainless Steel Wire (mV)
0.5	15	12	6	5
1.0	38	21	14	10
1.5	51	40	21	17
3.0	—	—	25	21



**Figure 10. Resistance as Measured by the Cu Sensors in the Varying Hole Diameters.**

levels out at different hole diameters. Between 1.0–1.5 in, the Cu wire's resistance decreased by 39%. After this point, a sharp leveling of the curve occurred, and the difference in resistance between 1.5 and 2.0 in was only 2%. For the stainless steel wire, the flattening, or 2% difference in resistances did not occur until the hole diameter reached between 2.0–2.75 in. The resistance continued to decrease for all the hole diameters tested for both the stainless steel mesh and carbon tows.

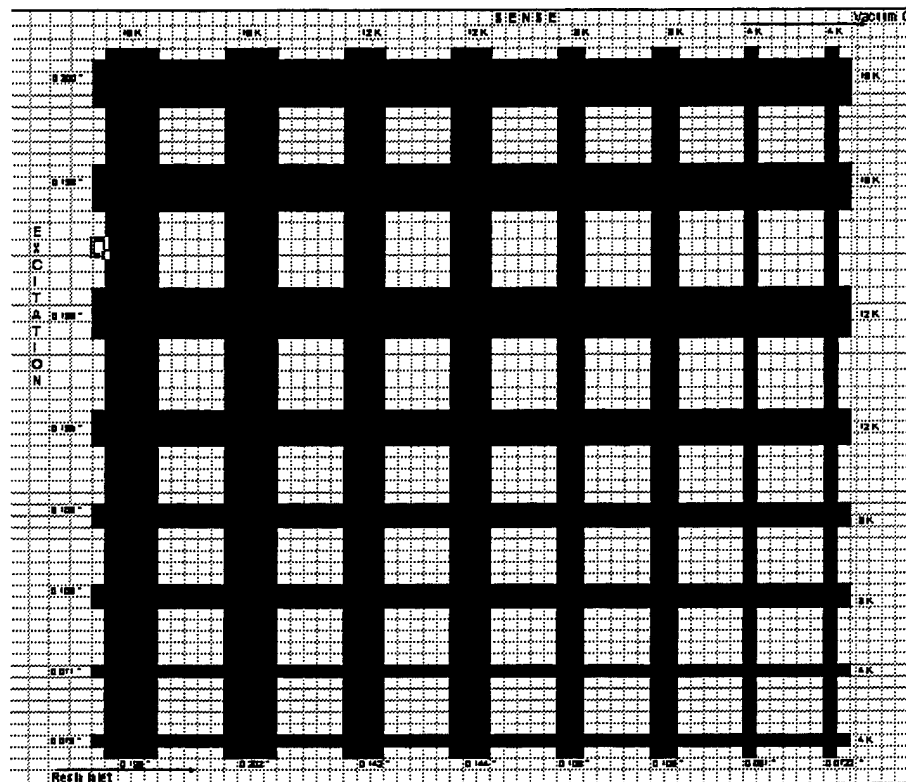
**4.3.3 Effective Area Comparison.** Upon further examination, the actual effective area of the node may be determined using equation [1]. As the sensor's exposed surface area increased, so did its effective area. As seen above, the data falls into two main clusters. In the initial slope, or in the region where the hole diameter is less than 1.5 in, the stainless steel mesh and carbon tow have twice the slope than that of the wire combination. Since the stainless steel mesh and carbon tow effective area rose at a much greater rate than that of the two wire sensors, it would be a greater advantage to horizontally separate the first pair by more than 1.5 in. If the upward trend continued past 1.5 in, the greater the horizontal separation, the greater the SMARTweave signal. At this point, it is significant to note (Table 3) that the largest stainless steel wire signal was approximately equal to the smallest stainless steel mesh signal. Also, the Cu wire signal at 1.5 in was almost half that of the carbon tow at the same hole diameter. Therefore, the magnitude of the desired voltage signal would need to be weighed against the grid density for the stainless steel mesh and carbon tows for horizontal separation distances greater than 1.5 in.

In summary, the 0.25-in-wide stainless steel mesh had the highest voltage signal per hole diameter, which indicated the effect of the sensor area. The stainless steel mesh and carbon tow appeared to follow approximately twice the slope of the Cu and stainless steel wire in the effective area-vs.-hole diameter comparison. The Cu wire should be separated by at least 1.5 in to achieve the greatest signal, while the stainless steel wires should be at least 2.0 in to avoid reduced sensor area. It is noted that if increased sensor density is desired, one can place them closer with the understanding that the signal will be decreased.

## 5. Sensor Area

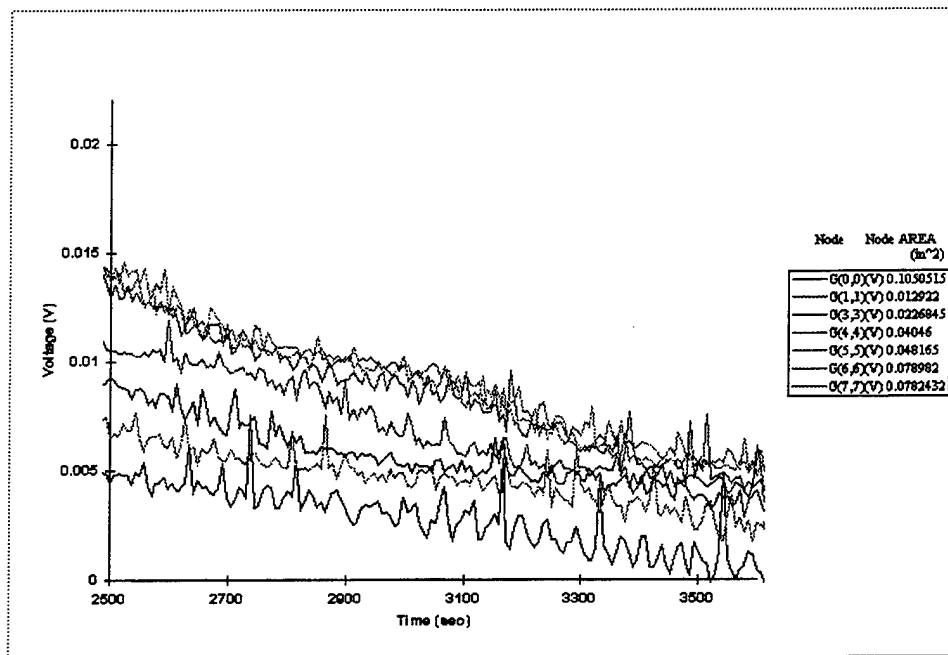
The sensors individual area was isolated next. To keep vertical and horizontal separation distances constant, carbon tows were used to test the effects of increasing sensor area on the SMARTweave voltage signal.

**5.1 Experimental Methods.** Three separate 13- × 13-in flat panels were fabricated using six plies of 7781 E-glass. Once again, the tightly woven fabric was used to ensure even separation distances. The sensors were separated by two plies to achieve the greatest voltage signal. Sensors were fabricated using the 4k tows, ranging from 4 to 16k. The increased area sensors were achieved by adhering the individual tows together with uncured Derakane 411-C50. The vinyl ester was first applied to the carbon tows, which were then twisted to ensure a better electrical contact between the individual tows. Next, they were uniformly flattened and placed within the part so that each had a regular thickness along the length/width of the flat plate. Duplicate sensors were placed every 1.5 in ranging from 4 to 16k starting at 1.5 in from all edges. As shown in Figure 11, the nodal area increased along the diagonal from the resin's inlet to the vacuum outlet. Silver conductive paint was used to adhere the tows together over the last 2.5 in on the outside of the vacuum bagging. The part was double vacuum-bagged to insulate it from the metal tool and any electrical noise of the room.



**Figure 11. A Schematic of an Experiment to Determine the Effect of Differing Cross-Sectional Areas.**

**5.2 Results and Discussion.** Figure 12 depicts an expanded view of SMARTweave's voltage vs. time along the diagonal of the carbon tow grid. The signal increased with the increasing nodal area. In fact, there is a direct proportionality between the nodal area and SMARTweave signal at the point of infusion, where diffusion limitations from crosslinking are minimal. This area of the curve correlated most directly to the uncured 411-C50/0.2 weight-percent CoNAP resin system. At the largest node (7,7), the initial SMARTweave signal equals 35 mV, while the smallest node (0,0) had a signal 7 times less of 5 mV. Significantly, the total nodal surface area also varied by 7 times. For carbon tows, there appeared to be a direct relationship between the SMARTweave signal and area during the initial stages after infusion.



**Figure 12. Degradation of Signal as the Area of Conduction Is Reduced.**

**5.3 Vertical Separation Distance.** The effects of vertical separation were investigated in an in-process environment.

**5.3.1 Experimental Methods.** A 27- × 14-in flat panel was fabricated using 18 total plies of 7781 E-glass. The finely woven 7781 was chosen so that a consistent separation distance could be

achieved. Twenty-two 4k carbon tows with Silver conductive paint on the last 2.5 in were used as the sensor material because of ease of lay-up and lack of coiling properties. Sensors were spaced 1.5 in apart, starting 2 in from all edges. Six excitation sensors were placed on the third ply from the top (all on the same horizontal plane). Sensors 0–7 were separated at increasing increments of two plies ranging from 2–16-ply separation distances. Senses 8–15 had the same setup as 0–7, thereby serving as repeated trials. Each ply of fabric represented 0.011 in. The part was double vacuum-bagged to insulate from the metal tool. The resin system consisted of 1,640-g 411-C50, 34.036-g Trigonox 239A, and 3.444-g CoNAP.

**5.3.2 Results and Discussion.** In comparing voltage vs. time along an excitation line, no significant difference can be seen in the SMARTweave signal. Repeated trials showed that vertical separation distance does not play a major role in the strength of the SMARTweave signal.

## 6. Conclusions

The conclusions drawn based on the results will be presented in logical order. To complete the investigation, the criteria defined will be acknowledged.

First, with respect to the horizontal separation distance, it was shown that each sensor material had a range in which the signal increased as the horizontal area increased. Then, at a point, the voltage stops increasing with an increase in area; this area should be used as a minimum spacing to ensure maximum SMARTweave signal. However, if better grid definition is required, it can be accomplished with the understanding that the signal will not be at its maximum potential.

Second, the area of conduction of the sensor type has a direct correlation on the SMARTweave signal. If the cross-sectional area of conduction is increased, by going from a 4k carbon tow to an 8k carbon tow, the signal can be increased.

Third, the vertical separation has been shown to have negligible effects on the SMARTweave signal.

Finally, coupling the seven criteria used to determine the optimal sensor material, carbon tows for glass composite parts appear to be the most effective sensor. Not only is it easy to lay up, but it also produces a strong signal, may easily be woven into the fabric, and can have varied areas. Although the stainless steel wire mesh produces a strong consistent signal, the sharp edges produced a problem in the laying up of the part as well as its cost. Both these issues need to be solved before it is implemented into the SMARTweave package.

## **7. Future Work**

The advancement of the technology associated with the SMARTweave system needs to continue. Work can be done in several areas. First, there are some interesting effects that are a function of the data acquisition system and they need to be understood. Second, further research needs to be put into more and different sensor materials. Finally, a novel idea came out of this research—the ability to use the in-situ sensor grid as a damage detection system.

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